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Subsidence and Its Surface Manifestations at the Weeks Island SPR Facility

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Abstract

The ground surface elevation change data measured over the storage mine at the Weeks Island Strategic Petroleum Reserve (SPR) site during the last 16 years has been studied and analyzed. The subsidence rate is not constant with time and while the subsidence rate appears to have increased slightly during the past several years, recently the rate has increased more dramatically. The most recent increase came at a time when the SPR storage mine had been emptied of oil and was in the process of being refilled with brine. Once the mine approached refill completion, the subsidence rate has diminished. The recent greater subsidence rates are believed to be the result of increased pillar shortening in the two mine levels. Damage to surface structures that has been observed during the past 12-18 months is attributed to the continued subsidence and differential subsidence across structures. Structural damage is characterized at Weeks Island according to a number of deformational modes associated with subsidence. The responsible mechanisms are discussed in this paper and will be used to aid further subsidence model development.

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Introduction

The Weeks Island salt dome is located 14 mi south of New Iberia, Louisiana, and is the central dome in the Five Islands chain, along with Belle Isle, Cote Blanche, Avery, and Jefferson Island. All five have been mined because of their near-surface salt, and their logistical advantage near the Gulf of Mexico and the Intracoastal Waterway. Belle Isle and Jefferson Island are now closed to mining because of deliberate and inadvertent flooding, respectively.

The sediment cover at Weeks Island consists of deltaic alluvium and is about 185 ft thick over the top of salt. The water table conforms generally to sea level over the dome but fluctuates somewhat with topography and frequent torrential rains.

The Weeks Island Strategic Petroleum Reserve (SPR) facility is a former conventional two level room and pillar mine (Figure 1) purchased by the Department of Energy (DOE) from Morton Salt for the purpose of storing SPR oil. The mine was originally opened in 1902 and salt was extracted commercially until 1977, at which time Morton Salt developed a new mine immediately adjacent to the northwest while the older workings were converted for oil storage. The mine stored approximately 73 million barrels of crude oil from 1981 to 1996, at which time the removal of oil began as a result of the decision to decommission the site.

Although not the subject of this report, sinkholes can form as a result of mine local subsidence. A sinkhole measuring 36 ft across and 30 ft deep was first observed in the alluvium overlying the salt dome in May 1992. Based on initial surface appearance and subsequent reverse extrapolation of growth rates, it was already about a year old at discovery. A second and much smaller sinkhole was identified in early 1995, nearly three years later. Their positions are located directly over the edges of the SPR oil storage chamber. The association of sinkholes with mines is well established. However, this occurrence suggested that groundwater influx into the mine was causing salt dissolution at depth, with associated collapse of soil at the surface (Neal, et al., 1998).

Since January 1983, the subsidence monument elevations at the Weeks Island site have been surveyed 15 times. Bauer and Neal (1997) and Bauer (1999) have most recently reported on the earlier survey data. Figure 1 is a base map of a portion of the Weeks Island site showing the footprint of the oil storage facilities and locations of a portion of the monuments. The changes in elevation, the rates of subsidence, as well as projections of future elevation changes are presented. Of specific interest to the DOE at Weeks Island is the areal and localized subsidence rate of the surface. At Weeks Island, owing to general high elevations, absolute elevations are not of paramount importance.

At Weeks Island and SPR sites in general, elevation changes are primarily due to creep closure of caverns. General subsidence on the scale of the site or portions thereof is seen in the survey data taken. These subsidence measurements capture surface manifestations of creep closure of underground openings.

Subsidence is important because of general concerns for safety and site operations. Localized subsidence can adversely affect the infrastructure of the site. Site facilities (electrical, mechanical, and transportation systems, including hoist equipment, ventilation, pipe lines, roads, etc.) could be damaged. Severe subsidence can impact future operations of the overall facility. Subsidence at Weeks Island has resulted in salt fracturing and subsequent water leakage into the mine. This has led to sinkhole development, and as a consequence for the emptying of the facility of oil and planned decommissioning.

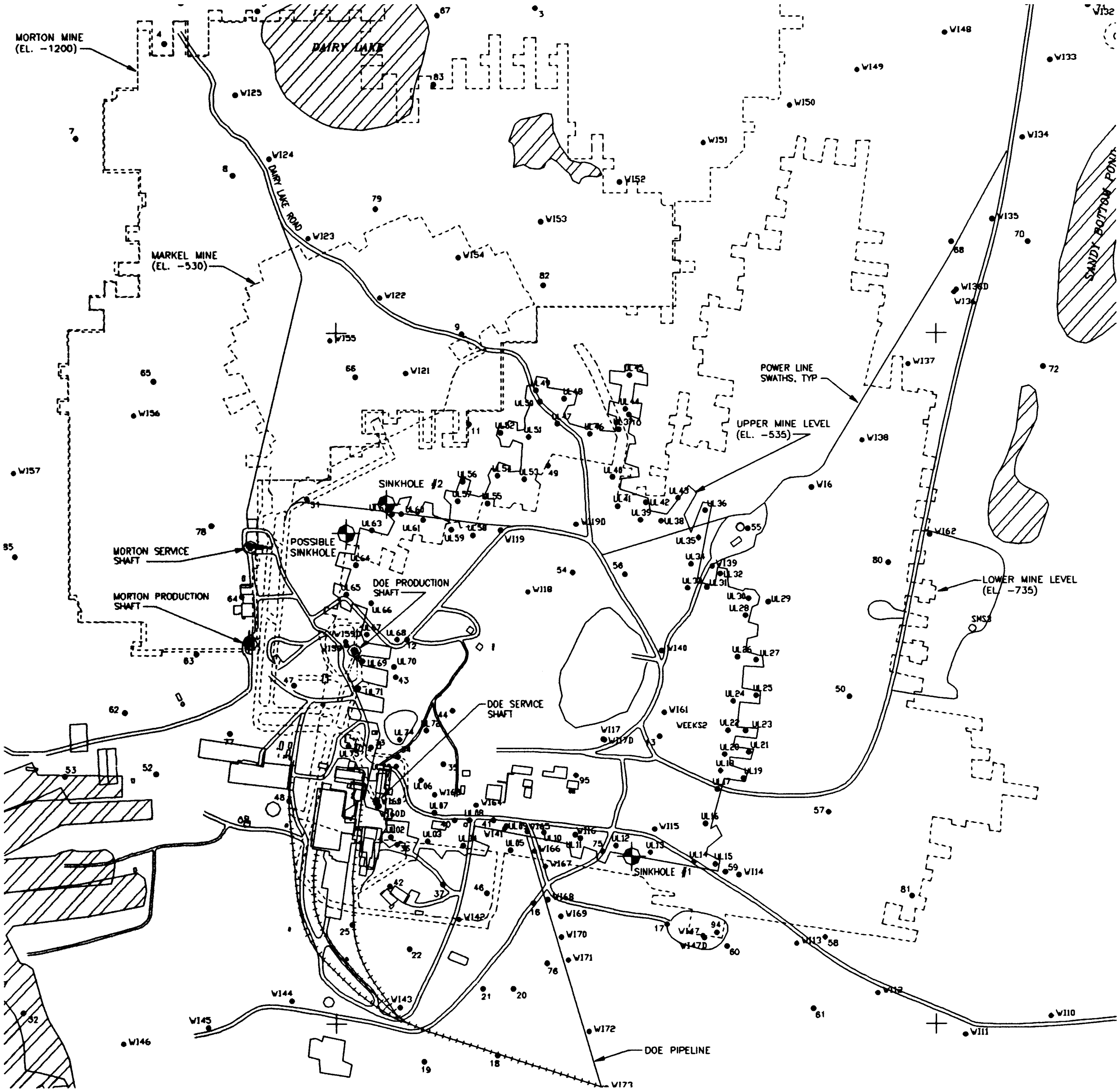

Figure 1. Site location map showing mine footprints and locations of newer subsidence monuments.

Procedures

Subsidence information is obtained in two ways, leveling surveys and visual observations. For the leveling surveys, elevation data represents the raw data. The measurements have been made at various time intervals. The survey includes about 109 data points within a near three square mile area. The number of data points varies between measurements because loss of monuments occurs through destruction and damage.

In practice, measurements of subsidence are difficult at best. The elevation of Monument Disc 23v32 is currently used to verify the elevation of WI-1, a local reference point for surveys. The elevation of WI-1 is verified at each survey. The reference WI-1 was installed before the February 1990 survey. WI-1 is located at the northeastern extremity of the survey network, outside the area affected by the oil storage and Morton mining. Since 1988, the leveling surveys have been performed to Second-Order First-Class accuracy, with allowable vertical closure error not to exceed 0.02 ft/mile$^{0.5}$. This means that for every mile long loop, the measurement must close to within 0.02 feet of the starting value. For loops less than a mile, the closure is accordingly smaller. Because WI-1 is so close to where measurements are made, the overall accuracy for measurements at the Weeks Island site is good. Furthermore, because survey loops are generally less than a mile, the accuracy is accordingly better than 0.02 feet. Osnes (1995) analyzed the surveying inaccuracies in the baseline data and found them to have a median value of about 0.01 ft and with approximately 95 per cent of the standard errors being less than 0.07 ft.

The survey accuracy influences the accuracy of the calculated subsidence rates. Relatively large errors in the calculated subsidence rates occur when the amount of subsidence between surveys is small. This is difficult to avoid outside of the mine boundaries where subsidence is small. Inaccuracies in the calculated rate directly over the mine can also occur, particularly when the survey periods are frequent.

Because of the extensive underground excavations, subsidence over the large-scale area (about three square miles) would be expected in the survey data. This type of subsidence captures gross effects of creep closure of underground openings. However, the surveys may also show precursors to localized subsidence. Although observations from extensive surface traverses across the site are scheduled quarterly, localized subsidence and effects that manifest themselves as potential safety hazards are more likely to be seen by workers, as happened in 1998. However, the detailed long term subsidence measurements provided by the surveys are important, especially because they permit the long term extrapolation of elevation changes into the future and provide a metric to evaluate numerical analyses (Hoffman and Ehgartner, 1996).

The earliest known survey data for Weeks Island dates back to 1931. The questionable quality and limited amount of information on the survey prevents further analysis, but the magnitude of subsidence as inferred from these measurements shows approximately 12 ft of subsidence over the central portion of the mine. The effects of deformation on this order can be observed at the site.

Site Observations

The authors have regularly visited Weeks Island and other salt mine operations in the Gulf Coast region. Unpublished observations have been made of subsidence related deformation of surface structures and associated maintenance/repair activities, with special attention to the surface facilities in the immediate vicinity of shafts. Observations of the nature described are not uncommon at salt mine facilities and demonstrate a number of deformational mechanisms associated with subsidence. What follows are descriptions of observations of deformations of site facilities at the Weeks Island site.

In Fall 1998 inspections of the Production Shaft building at Weeks Island were made in conjunction with other site related work (Bauer,1998a,b). Observations of the exterior of the building show striking compressional features on the northeast side of the building (displaced nail holes and folded and faulted fiberglass sheeting) as shown in Figure 2. The deformation is accommodated on the southwest side of the building with extensile features as indicated by stretched nail holes in the fiberglass sheeting, horizontal cracks in the basal blocks of the building, and vertical cracks in the airlock room as shown in Figure 3. In addition, the airlock room may be separating from the rest of the Production Shaft building.

These observations in themselves suggest only superficial damage to the building and do not indicate any loss in function of either the shaft building or the adjacent airlock building.

2a.

2b.

Figure 2a. Distant view of bent and sheared fiberglass panels on northeast side of hoist building.
Figure 2b. Compressed nail hole features on northeast side of hoist building.

From the above observations, it appears that the Production Shaft building is leaning to the northeast towards the center of subsidence over the mine. Evidence of the origin of this leaning can be seen inside the building. The floor may be described as an inner collar that comes right up to the shaft edge, and an outer collar area. In places there is a horizontal separation between the two collar segments as evidenced by Figure 4. Little to no relative vertical displacement was observed at this parted interface. The joint appeared to have been sealed at some time in the past with a bead of silicon joint compound. The joint now has more than half an inch of horizontal offset in places. Both the inner collar and outer collar are cracked, however, the outer collar appears to be much more heavily cracked.

The outer collar cracks first aroused workers attention more than a year ago, fostering a closer look at subsidence analyses (Bauer and Linn, 1998). At that time it was determined that about 2 inches of differential subsidence had occurred across the building foundation during the past 40 years.

2c.

2d.

Figure 2c. Oblique view of bent and sheared fiberglass panels on northeast side of hoist building.
Figure 2d. Close up view of sheared fiberglass sheathing and stretched (extended) nail hole features on northeast side of hoist building.

3a.

3b.

Figure 3a. Vertical crack in wall joining airlock room and hoist building (southwest side of hoist building).
Figure 3b. Horizontal foundation cracks on southwest side of hoist building.

3c.

3d.

Figure 3c. Vertical cracks in wall of airlock room on southwest side of hoist building.
Figure 3d. Stretched (extended) nail holes on southwest side of hoist building.

Knowledge of the details of this differential subsidence and crack patterns in the pad could allow one to determine a cause and effect relationship between the subsidence and slab cracking.

The cracked concrete pad shows some vertical displacement immediately above the shaft liner where the inner collar appears to be lifted about an inch. This amount of displacement is consistent with the amount of cracking in the 3 to 4 foot thick concrete pad. The fiberglass panels inside the building are buckled in places, a stair rail is bent and a steel joint is cracked adjacent to a bent steel member (Figure 5). The function of all of these elements has been maintained. These observations are not unexpected given the pad cracking. Some leaning of the building frame has likely occurred, and some non-structural elements have deformed in response.

Deformation immediately around the shaft itself was also observed (Figure 6). The lift guides are tied into two opposed massive horizontal timbers through an intervening steel plate. Immediately below where the guides are tied to the massive horizontal timber members there is a horizontal crack in each of the members. The crack in each opposing member appears widest (about 0.5") at the center of the timber and dies out at the ends. It appears that the timbers are being pulled upward from where they are fastened to the vertical guides. It is adjacent to the cracked horizontal timbers that the inner collar appears to be lifted off the timbers about an inch. One corner of the inner collar had localized deformation in the form of cracking and shear displacement. No cracks were observed in either of the cross timbers, which run perpendicular to those connected to the lift guides. Also, it is important to note that no cracks were observed in the vertical lift guide timbers. The function of the system is again retained.

Figure 4. Horizontal separation between inner and outer concrete collars, and cracks in collars inside Production Shaft hoist building.

Figure 5. Bent stair rail, bent steel member and cracked steel joint, and buckled fiberglass panels inside hoist building.

Previous work (Bauer and Linn, 1998) has been cited that gives a potential cause and effect relationship between subsidence and cracking observed in the concrete of the hoist building floor. The direction of leaning of the hoist building is consistent with subsidence gradient from a direction of less subsidence on the mine edge (west side of hoist building) to more subsidence (east side of hoist building), directly over the mine. As noted previously, phenomena of this nature are not uncommon in the vicinity of shafts at salt mines.

Figure 6a. Two views of vertical lift guide connected to massive horizontal (cracked) timber. Note vertical separation between inner collar and the top of the timber (about an inch). Also note lack of deformation in timber perpendicular to the cracked one.

Figure 6b. Two views of vertical lift guide connected to massive horizontal (cracked) timber on opposing side to Figure 6a. Note similar vertical separation between inner collar and the top of the timber (about an inch). Also note localized deformation in corner of concrete collar.

During a recent surface inspection (Bauer,1998a,b), evidence of possible effects of subsidence upon other DOE structures was observed. Some observations were made inside the DOE main complex that are indicative of damage to surface facilities. The brick fascia on the corners of the administration building has vertical cracks and attendant displacement. The concrete walkway on the south of the administration building and the one to the west of the old guard house has been cracked and displaced (Figure 7). A pipe support is sinking away from the pipe it is supposed to be supporting and a concrete abutment is rotating (Figure 8). These observations should be expected in facilities which overlie ground across which considerable differential subsidence has been documented. The function of these facilities has not been effected by the deformations present. Further, the observations have led to an increased awareness of subsidence and its effects on surface facilities, an increase in the frequency of subsidence measurements, and a more aggressive attitude towards brine refill of the mine at that time. Again these observed cracks in buildings and displacements in concrete walkways are likely the result of differential subsidence at the site.

7a. 7b. 7c.

Figure 7a. Administration building area: cracking and horizontal displacement of brick fascia.
Figure 7b. Administration building area: displacement of concrete walkway.
Figure 7c. Administration building area: cracking and displacement of concrete walkway.

8a. 8b.

Figure 8a. Pipe support separated from pipe it had been supporting.
Figure 8b. Concrete abutment that has undergone rotation.

Leveling Survey Results

The results of measurements of elevation data since May of 1983 are displayed in Figures 9-13. Subsidence rates are due to creep closure of the underlying oil storage facility and the adjacent Morton Mine.

From 1983-1990 the area surveyed was relatively small (about a quarter of a square mile) compared to the DOE property boundary, and contained only about twenty measurement stations (Figure 9). The subsidence rate averaged between 0 and 0.1 ft/yr during this time period, but only one station was located over the center of the mine used by the SPR for oil storage. The survey station array has been gradually increased since 1990 to currently include over a hundred stations (109 in 1998), some of which are located over the middle of the DOE facility. Each year the number of stations vary because some cannot be found or have been destroyed.

Figure 10 presents subsidence rates for the 1990-1992 time period for the entire nearly three square mile area currently being studied. The extended array encompasses the DOE facility, a portion of the Morton mine facility to the northwest as well as more stable areas to the east and southeast of the DOE facility. An important peripheral observation made possible with these data is the consistent continued rise of the Weeks Island salt dome. The rate of uplift is about 0.01 ft/yr. Also evident for the first time with these measurements are the greater rates of subsidence over the DOE mine area and rates over the Morton facility. These greater rates are recorded for the first time possibly because of the increased number of monuments added in this area and because of the greater accuracy ascribed to the survey.

From 1992 to 1995 (Figure 11) the subsidence rates appear very similar to the previous time period with the exception that a localized increased subsidence rate is observed in the northern part of the DOE facility area. This northern area "anomaly" disappears in the 1995-1996 time frame (Figure 12). The observed rates over the DOE and Morton facilities persist, with an increase up to 0.2-0.3 ft/yr range over the DOE facility, reflecting the drawdown of the oil from the mine which started in November 1995.

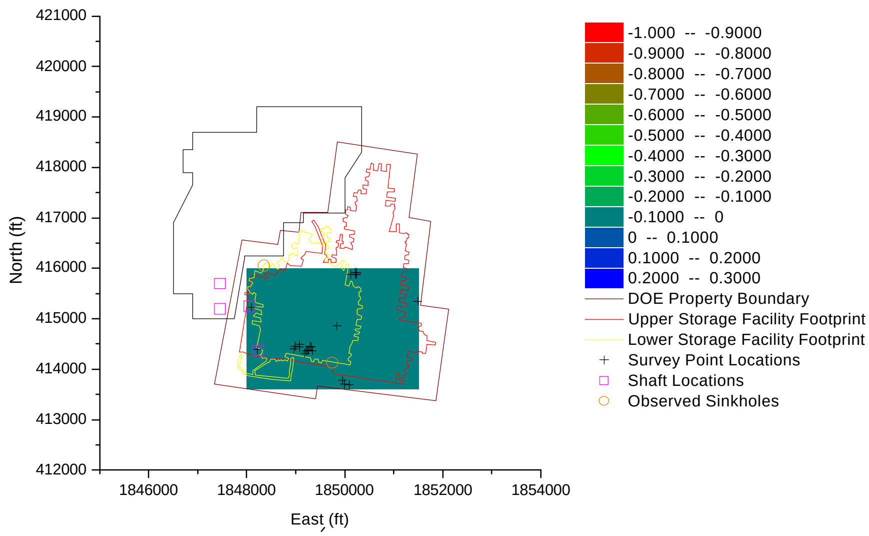

Figure 9. Weeks Island subsidence rates (ft/yr) 11/83-2/90.

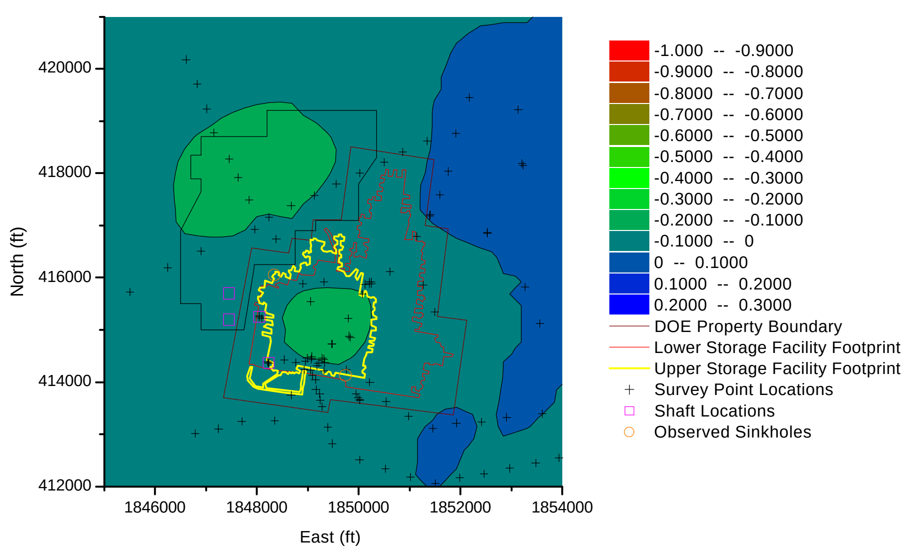

Figure 10. Weeks Island subsidence rates (ft/yr) 2/90-12/92.

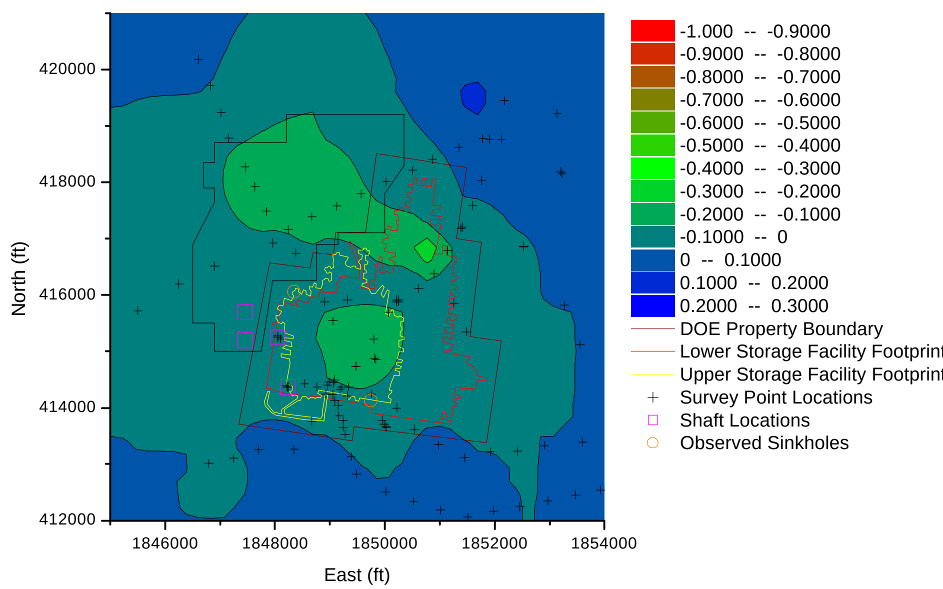

Figure 11. Weeks Island subsidence rates (ft/yr) 2/92-2/95.

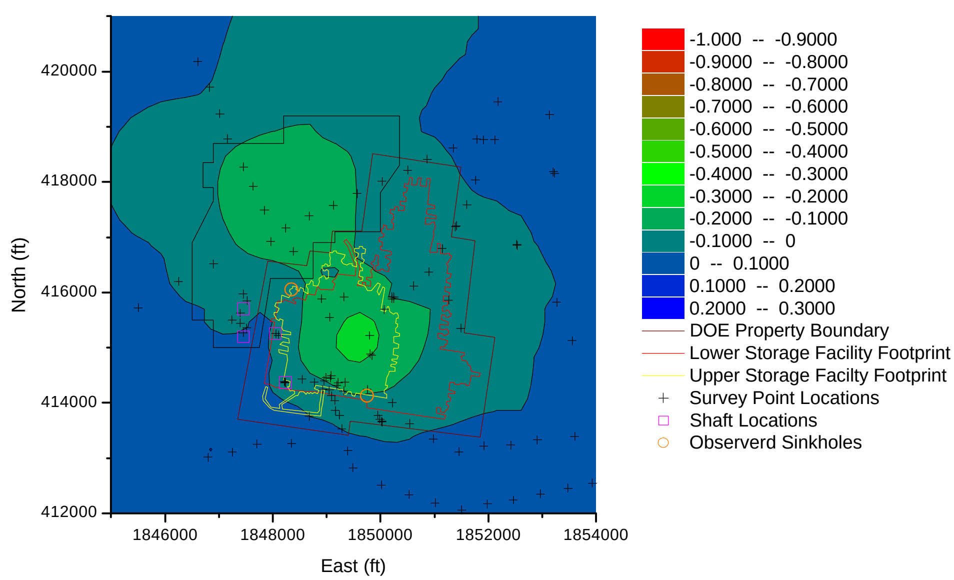

Figure 12. Weeks Island subsidence rates (ft/yr) 2/95-12/96.

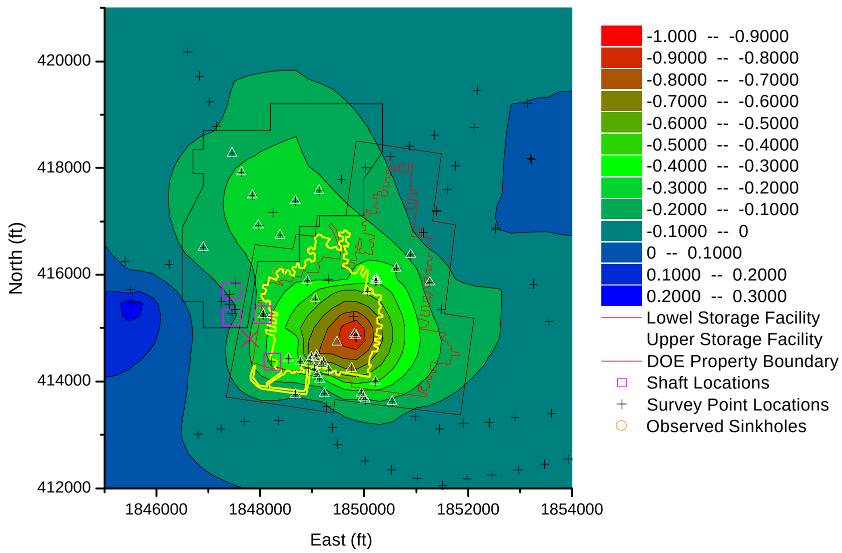

Figure 13. Weeks Island subsidence rates (ft/yr) 12/96-9/98.

Between 12/96 and 9/98 the subsidence rates over the DOE facility increased markedly (Figure 13). Maximum subsidence rates are near 1 ft/year (near subsidence monuments Weeks 2 and WI-61 located in the southeast corner of the area denoted by “Upper Storage Facility”). Subsidence rate increases were observed for most of the DOE facility area, in the 0.3 to 0.5 ft/yr range. In summary, local rates increased by a factor of up to four to five, whereas overall rates increased by a factor of two to three. Subsidence rate increases of two to three are also observed to the northwest, over the Morton facility. The white triangles in Figure 13 represent stations that experienced a factor of three or greater increase in subsidence rate. The recent increase in subsidence rates is consistent with the data collected local to Sinkhole #1 for the time period of early-mid 1997. That data showed that subsidence near Sinkhole #1 was consistent with observed subsidence over other areas of the mine. At that time (prior to the most recent subsidence data), the increase in rates observed was attributable to the emptying of the mine of oil. For the recent measurements, increased subsidence is observed at the Weeks Island site predominantly over the oil storage facility and Morton facilities. The high rate increases found recently over much of the DOE and Morton facilities are potentially due to emptying the mine and subsequent refill with brine.

Subsidence Mechanisms

The change in the subsidence rate over the DOE facility is related to the creep closure of the mine. The mine closure rate is influenced by several mechanisms, including the stress state which has changed in the mine and storage facility over time.

At the DOE facility, the stress state is determined by the facility depth, internal geometry, and fill condition (oil filled, or partially oil filled, empty, brine filled or partially brine filled). The internal geometry has remained relatively constant since the DOE assumed ownership of the facility. However, the fill condition has changed with time. The mine was empty until 1982. It was oil filled by 1983 and remained filled until November of 1995. At that time, the removal of oil from the mine began and took 9 months to complete. Since that time, the mine has had various levels of brine refill to accommodate several oil skimming phases. Changes in the stress state during brine removal were predicted to result in a 60% subsidence rate increase (Hoffman,1994). The predicted rate agreed closely with the measured rate at that time. However, the analyses cannot account for the measured subsidence rate increase during brine fill. Figure 14 shows the relationship between subsidence rates (measured and predicted) with time and the fluid level in the mine.

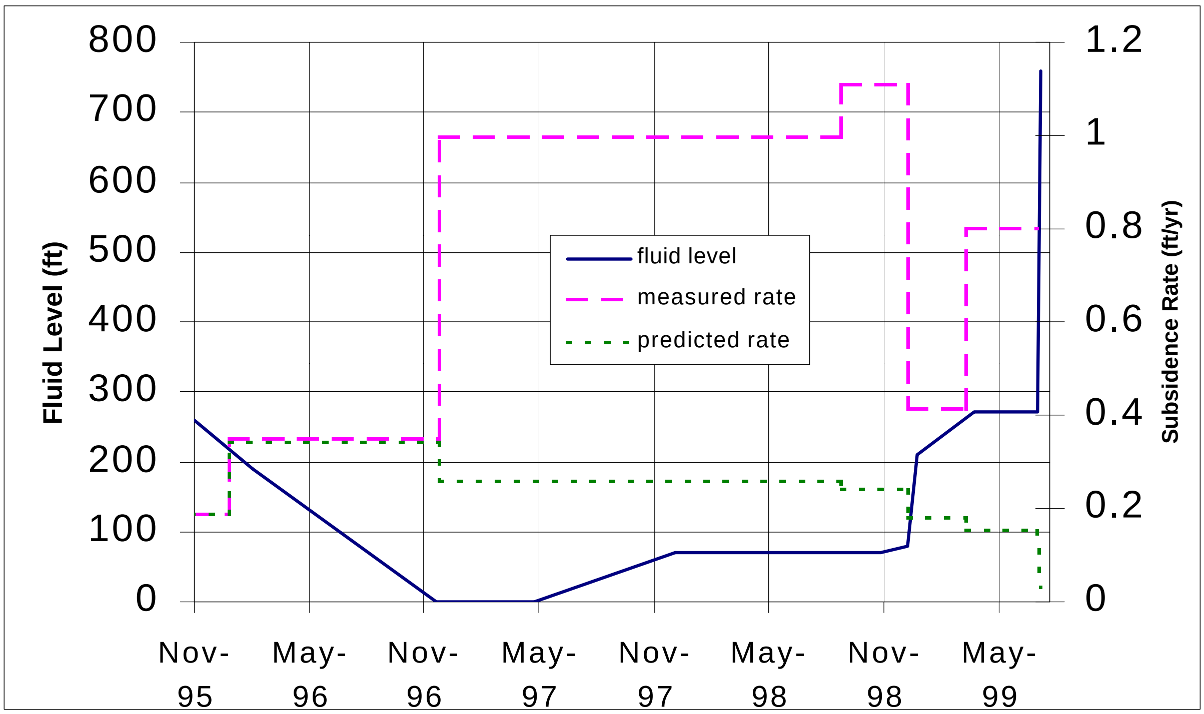

Figure 14. Relationship between subsidence and fluid level in the mine. The predicted rates are an average for the time period between leveling surveys and are based on stress dependent salt creep models .

The brine used for refill was about 80% saturated. This brine quality has probably facilitated some dissolution of the mine surfaces, but these surfaces consisted of spalled and damaged salt, which provided little to no structural support, and piles of crushed salt which were spread out over the mine floor. Therefore, dissolution is believed to have a small role in subsidence changes at the site. Figure 15 shows some pictures taken in the mine prior to oil fill. The spalled pillars had no adverse consequence on mine stability. This is evidenced by the long history that the pillars have in supporting the ground and stability is inferred through the relatively small and steady subsidence rate measured prior to oil withdrawal. Spalling is believed to result from tensile stresses developed in the salt after mining. After the salt spalls, a more favorable pillar geometry forms and further tensile stresses are not predicted (Hoffman and Ehgartner,1996). The ability of the finite element models to simulate the subsidence rates during oil fill and drawdown suggests that the deformation mechanism is controlled through creep. During the drawdown, mine pressure returned to its previous atmospheric level and no increase in subsidence was noted beyond that predicted. As the mine was brine filled, support was re-established on the pillar and roof surfaces. The added pressure was expected to decrease the subsidence rate on the order consistent with that previously measured when the mine was full of oil. The known pressure dependent mechanisms (elasticity, creep, and damage) should have decreased the subsidence rate to approximately 0.03 ft/yr. However, the subsidence rate increased. This suggested that another mechanism was controlling salt deformation and hence subsidence.

The increased subsidence rates over the Weeks Island mine can be explained by the moisture introduced to the salt as a result of brine fill. Moisture is known to increase the ductility and creep of salt, in some cases by orders or magnitude (Ehgartner, 1999). The mechanism, although well quantified in the laboratory and through field observations, is difficult to model. It is difficult to predict how long the measured subsidence rates will remain above those predicted using the stress based models. Case studies on flooded mines, such as those at Belle Isle and Jefferson Island, show that within years the measured subsidence rates reduce to those predicted by stress controlled creep models.

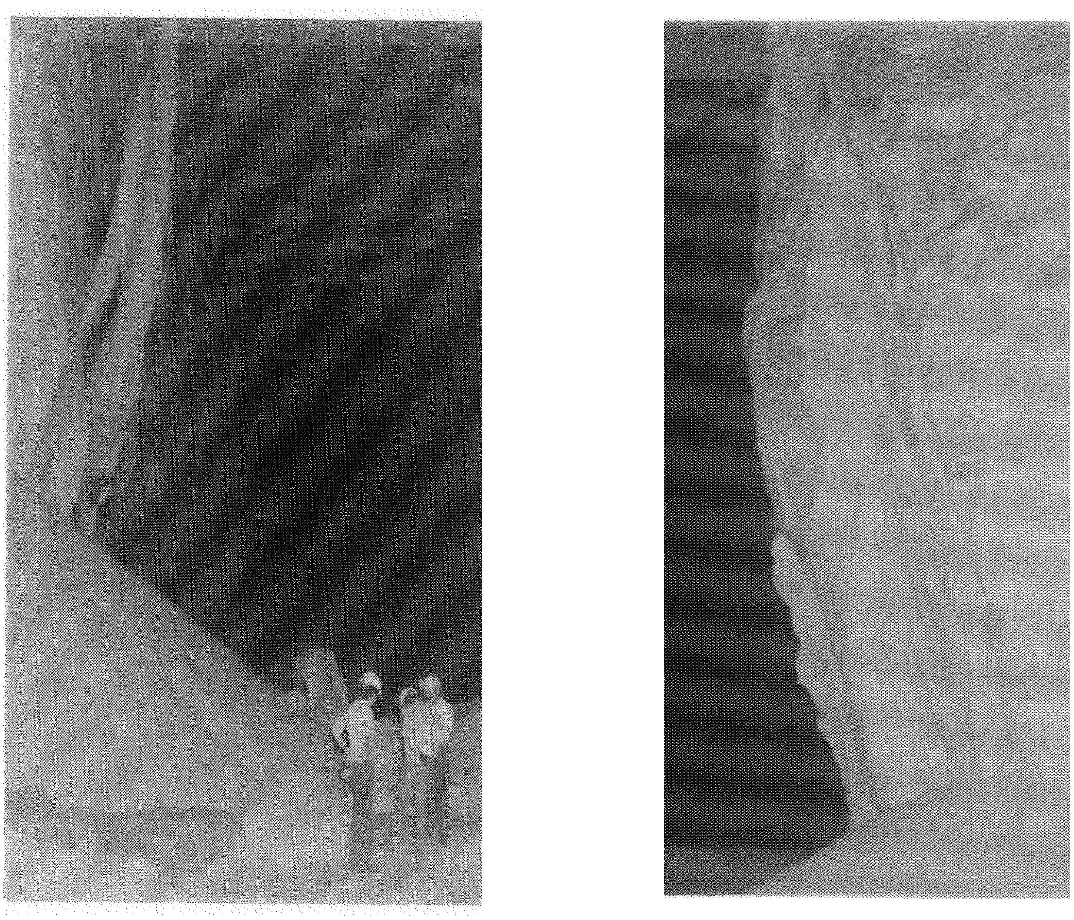

Figure 15. Photos of Weeks Island mine taken in 1977 prior to mine conversion for oil storage.

Summary and Conclusions

The elevation change data measured at the Weeks Island SPR site over the last 16 years has been studied and analyzed. Although the subsidence rate has increased only slightly in the past years, the rate has recently increased more dramatically. The recent increase comes at a time after the SPR storage mine was emptied of oil and was in the process of being refilled with brine. This increase is beyond that expected and cannot be predicted through the current models of creep. In fact a new mechanism is required to explain the effect. In particular, moisture is known to increase ductility and creep of salt, and thus subsidence.

Damage to surface structures that has been observed during the past 12-18 months is attributed to the continued subsidence and differential subsidence across structures. This type of deformation is not uncommon at other shaft building facilities above Gulf Coast salt mines. Damage of this type should be anticipated at SPR facilities wherever differential subsidence of sufficient magnitude occurs. None of the observed damage has caused loss of function of the various facilities.

This paper points to a continued need to routinely collect a complete set of elevation data at SPR facilities. The data collected has provided information to the project that was unanticipated by previous analyses. Thus, subsidence data can be used not only to compare with future analyses, but also as an important diagnostic tool.

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